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Performance of Dense Graded Asphaltic Concrete Using Nanosilica Modified Bitumen

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Abstract. Flexible pavements are constructed to last for its design life, therefore, a good and durable asphalt surface layer is required. However, flexible pavements using dense graded asphaltic concrete have some shortcomings such as prone to rutting when heavy loads are applied at high ambient temperatures. One of the ways to improve the performance of dense graded asphaltic concrete is to modify the bitumen using nanosilica. Among the properties of nanosilica that is advantageous to improve the bitumen is strong absorption, large surface area and excellent stability. The objective of this study is to investigate the use of nanosilica as a bitumen modifier to improve the moisture susceptibility and rutting resistance of dense graded asphaltic concrete. Bitumen PEN 60/70 was modified with nanosilica at 2% by weight of bitumen. The performance of the asphaltic concrete specimens was then evaluated in terms of its moisture susceptibility, resilient modulus and rutting resistance. The results obtained from the testing showed that the addition of nanosilica increased the resilient modulus value and reduced the rutting depth of dense asphaltic concrete mixes, while achieving the required moisture resistance. It concludes that the addition of nanosilica in the bitumen improved the performance of dense asphaltic concrete mix.

1. Introduction

The ever-increasing numbers of heavy vehicles with increased axle loads on the roads today placed high demands on the pavements to withstand the high stresses imposed from these vehicles. Good pavement design and timely maintenance enable flexible pavements to withstand these demands but special attention is required on highly stressed areas particularly the roads and highways with very high percentage of heavy vehicles and loaded with heavy freight. Bitumen modification offers a solution to provide a longer service life on these roads and reduce the frequency of maintenance required [1].

Researchers around the world have investigated various kinds of modifiers to modify the bitumen in order to improve its performance such as polymer. The polymer modifiers used include Styrene-Butadiene-Styrene (SBS), Styrene-Butadiene-Rubber (SBR), Styrene-Ethylene-Butylene-Styrene (SEBS), crumb rubber, and Ethylene Vinyl Acetate (EVA) [1]. These studies found that the use of polymer in asphalt modification can improve the rheological properties in terms of phase angle (δ) and dynamic modulus (G*), resistance to fatigue cracking, rutting and moisture susceptibility. Although

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these polymers all improved bitumen properties to some extent, there are still some drawbacks limiting their application such as high cost, low ageing resistance and poor storage stability [2]. Therefore, there is a need for further explore the use of other materials such as nano materials to improve the performance of bitumen and at the same time overcome these drawbacks.

Nanotechnology is the creation of new materials, devices, and systems at the molecular level as the phenomena associated with atomic and molecular interaction strongly influence the macroscopic material properties [3]. Nanomaterial/nanoparticle is a material with least one dimension is on the nanometer scale that is one billionth of a meter (10-9 m).

Nanomaterials that have been investigated for use in asphalt mixes include nano-clay, carbon nanotube and carbon nanofibre, nano-TiO2, nano-silica and nano-alumina [4]. Nanoclay was found to improve the viscosity and complex modulus (G*) value of bitumen. Carbon nanotube (CNT) is a one-atom thick sheet of graphite rolled up into a seamless hollow cylinder with a diameter of the order of one nanometer. The addition small percentage (around 1.5%) of CNT helpful in increasing the failure temperature, elastic modulus, complex modulus and rutting resistance of the bitumen after RTFO aging.

Silica is the dioxide form of silicon, SiO2 that is naturally occurring, such as quartz sand, rocks, and clays, and is widely used in industries to produce silica gels, colloidal silica, and fumed silica [5]. Nanosilica (NS), derived from processed silica, has a maximum dimension of about 30 nm. An inorganic material possesses beneficial properties such as large surface area, good dispersal ability, strong adsorption, high chemical clarity and excellent stability [6]. NS has been widely used in polymer, concrete and asphalt binder as inorganic filler to improve the properties of polymeric, mechanical and bituminous materials. In bitumen modification, a study by Yao [7] showed that the addition of NS improved anti-aging property, rutting and fatigue resistance of asphalt mixture. In addition dynamic modulus, flow number and rutting resistance of asphalt mixture also significantly improved.

Since NS promises improvements in properties for bitumen modification, therefore, in this study NS was used as a modifier to modify bitumen. Bitumen PEN 60/70 was modified with different concentrations of nanosilica. The modified bitumen was then used in dense asphaltic concrete and the performance of the asphaltic concrete specimens was then evaluated in terms of its moisture susceptibility, resilient modulus and rutting resistance. The objective of this study is to investigate the use of nanosilica as a bitumen modifier to improve the performance of dense graded asphaltic concrete in terms of moisture resistance, stiffness and rutting resistance.

2. Methodology

The properties of aggregates and bitumen used for the study were first tested to ensure compliance with the specifications. Marshall mix design method was then used for sample preparation using both the unmodified Pen 60/70 bitumen as control sample and the modified bitumen (2% NS by weight of bitumen). The optimum bitumen content was then determined. Finally, moisture susceptibility, resilient modulus and rutting tests were carried out to evaluate the performance of the dense asphaltic concrete mixes.

2.1. Materials

In this study, bitumen of 60/70 penetration grade was modified using 2% NS by weight of the bitumen. The bitumen was supplied from Petronas Berhad. The influence of NS on bitumen was determined by the softening point test, penetration test and ductility test. The aggregate used was obtained from Kajang Rock Quarry, Selangor. The aggregate tests conducted for this study are Los Angeles Abrasion Value, Aggregate Impact Value, Aggregate Crushing Value and Flakiness Index Value. Portland cement was used as filler additive to the mixture. The bitumen and aggregate used complied with the requirements as per PWD Malaysia's Specification for Road Works (JKR/SPJ/2008-S4). The properties of the bitumen, aggregates and liquid, gel type NS is shown in Table 1, Table 2 and Table 3.

Table 1. Physical properties of bitumen.

Test	Test result
Softening point (°C)	48-56
Penetration (0.1 mm)	60-70
Ductility (cm)	>100

Table 2. Properties of aggregates.

Test	Test result
Aggregate crushing value	18.3%
Aggregate Impact Value	20.6%
Los Angeles Abrasion	27.0%

Table 3. Properties of nanosilica.

Parameter	Specification value
Appearance	Slight milky transparent to translucent liquid
SiO2 (wt%)	30±1%
Na2O (wt%)	0.5%
pH (20°C)	8.5-10.5
Density (20°C, g/cm3)	1.19-1.22
Particle size (nm)	10-15

The bitumen was modified using a mechanical mixer. Asphalt binder was placed in a container and heated up to 155oC using a hot plate. NS was gradually added to the asphalt binder while stirring with a mechanical stirrer at a speed of 2000 rpm. The mixing process continued for one hour to achieve uniform dispersion of NS. The optimum amount of NS was determined based on a previous study by the author, after evaluation of the physical properties of the modified bitumen (penetration, softening point, ductility, viscosity and storage stability). The optimum NS content was found to be 2% by weight of bitumen as shown in Table 4. In addition, further evaluation were carried out on the modified bitumen for morphological properties (using atomic force microscopy and x-ray diffraction), rheological properties (using dynamic shear rheometer) and chemical properties (using Fourier transform infrared spectrometer) [8,9].

The AC14 aggregate gradation used was in accordance to PWD Malaysia's Specification for Road Works JKR/SPJ/2008-S4[10]. Table 5 shows the aggregate gradation as per the specification. The middle gradation line between the gradation limits was used for this study.

Table 4. Physical properties of nanosilica modified bitumen

Physical Properties	Nanosilica Concentration (% by weight of bitumen)	
	0%	2%
Softening point (°C)	52.3	60.3
Penetration (dmm)	65.0	41.1
Ductility (cm)	140.0	70.2
Viscosity (Pa)	0.7	0.9
Storage stability	0	0.2
Penetration Index	0.02	0.62
Penetration Viscosity Number	0.103	-0.054

Table 5. Aggregate Gradation for Samples (PWD Malaysia, 2008).

Mix Designation	AC 14 Gradation (Specification)	AC14 Gradation used (mid-gradation)
B.S Sieve	% Passing By Weight	% Passing By Weight
20 mm	100	100
14 mm	90 -100	95
10 mm	76 – 86	81
5.0 mm	50 - 62	56
3.35 mm	40 - 54	47
1.18 mm	18 - 34	26
425 µm	12 - 24	18
150 µm	6 - 14	10
75 µm	4 - 8	6

2.2. Preparation of samples

The laboratory testing carried out in this study include Marshall mix design to determine the optimum binder content, moisture susceptibility test, resilient modulus test and rutting resistance tests to evaluate the performance of the dense asphaltic concrete mix.

2.2.1. Marshall mix design. Marshall samples were prepared at 4.0%, 4.5%, 5.0%, 5.5% and 6.5% bitumen contents for 0% NS (control) and 2% NS asphalt mixtures. The samples were prepared in accordance to ASTM D6926 to determine the Optimum Bitumen Content (OBC) using the Marshall Test method. Before the mixing process, the bitumen was heated to a temperature of 155ºC. The mix was compacted at a temperature of 135 ± 5ºC using the standard Marshall compactor with 75 blows for each face. Marshall tests were carried out on the samples and volumetric analysis were carried out on the results obtained from the tests in accordance to ASTM D1559. The average value of bulk specific gravity, stability, flow, VFA and VMA obtained separately were plotted against the bitumen content and smooth curve were drawn through the plotted value. The determination of optimum bitumen content (OBC) for ACW-14 was determined by averaging the optimum bitumen contents as specified in JKR/SPJ/2008-S4.

2.2.2. Moisture susceptibility test. The Modified Lottman test was performed to evaluate the moisture susceptibility of the mixes in accordance with the procedure described in AASHTO T 283. Samples for the test were prepared at 7 + 0.5% air voids. Three samples are selected as a control and tested without moisture conditioning; and another three samples were selected to be conditioned by saturating with water at 70-80 percent followed by immersing in water for 24 hours at 60ºC in a water bath. The samples were then tested for indirect tensile strength (ITS) by loading the samples at constant head rate (50 mm/minute vertical deformation at 25ºC) and maximum compressive force required to break the samples were recorded. Tensile Strength Ratio (TSR) results were determined by comparing the indirect tensile strength (ITS) of unconditioned samples with the control samples. Retained tensile strength ratio (TSR) was used with 80% as the boundary between mixtures resistant and sensitive to moisture.

2.2.3. Resilient modulus test. Indirect tensile repeated load test was used to determine the resilient modulus. The test used the UTM-5P machine. The resilient modulus test was conducted to measure the stiffness modulus of the design asphalt mixtures. All samples were conditioned for 3 hours at a temperature of 25ºC. The test was performed in accordance with ASTM D 4132. Three pulse repetition periods was applied, 1000 ms indicates low traffic volume road (high speed), 2000 ms for medium traffic volume road while 3000 ms is high traffic volume road (slow speed). The compacted cylindrical asphalt mixture was subjected to diametrical repeated loading of 900 N and two points was taken on different axis at each sample.

2.2.4. Rutting resistance test. The Asphalt Pavement Analyzer (APA) device was used to determine the rutting resistance of asphaltic concrete mixes. In this study, asphaltic concrete mixes containing with 0% and 2% NS were prepared with the weight of aggregate of 2965g and compacted at $7 \pm 5\%$ air voids. The specimens were tested at 60°C of temperature with a hose pressure of 100 ± 5 psi and wheel load with 100 ± 5 lb. This test was carried out based on the standard procedure given in AASHTO T340. Figure 1 shows the Asphalt Pavement Analyser.

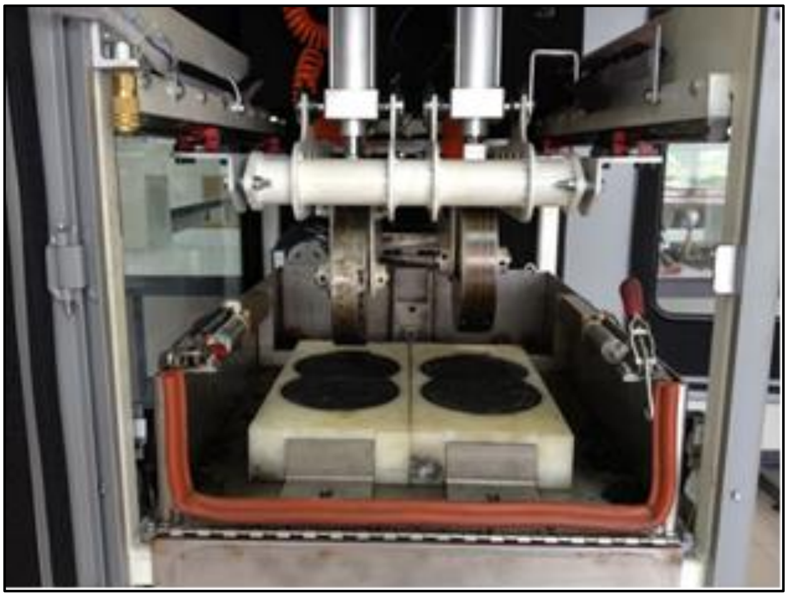

Figure 1. Asphalt Pavement Analyzer for rutting resistance test.

3. Results and discussion

3.1. Optimum binder content

Marshall Test was carried out on the samples and volumetric analysis was carried out on the results obtained from the tests. The average value of bulk density, stability, flow, VFA and VMA obtained separately were plotted against the bitumen content and smooth curve were drawn through the plotted value. The OBC was determined from the arithmetic mean of the results from the five curves plotted and the value was cross-checked with the limits set in Public Works Department specification. Table 6 shows the OBC for both samples. The OBC obtained for 0%NS samples is 4.92% while the OBC for 2%NS samples 4.96%.

Table 6. Optimum bitumen content determination.

Property	0%NS	2%NS
Peak of curve taken from the graph bulk specific density	5.05	5.20
VIM equals to 4.0% from VIM graph	4.75	4.80
VFB equals to 75% from VFB graph	4.95	4.89
Peak of curve taken from the stability graph	4.70	4.65
Flow equals to 4mm from flow graph	5.15	5.25
Average OBC	4.92	4.96

3.2. Moisture susceptibility

Figure 2 shows the results of Indirect Tensile Strength (ITS) for dry and wet conditioned samples for both 0% and 2% NS asphaltic concrete mixes. For dry conditioned samples, 2% NS mix has higher ITS value (1147 kPa) compared with 0% NSMB mixes (1134 kPa). However, for wet conditioned samples with 0%NS has higher ITS value of 972 kPa compared with 927 kPa for 2% NS mixes.

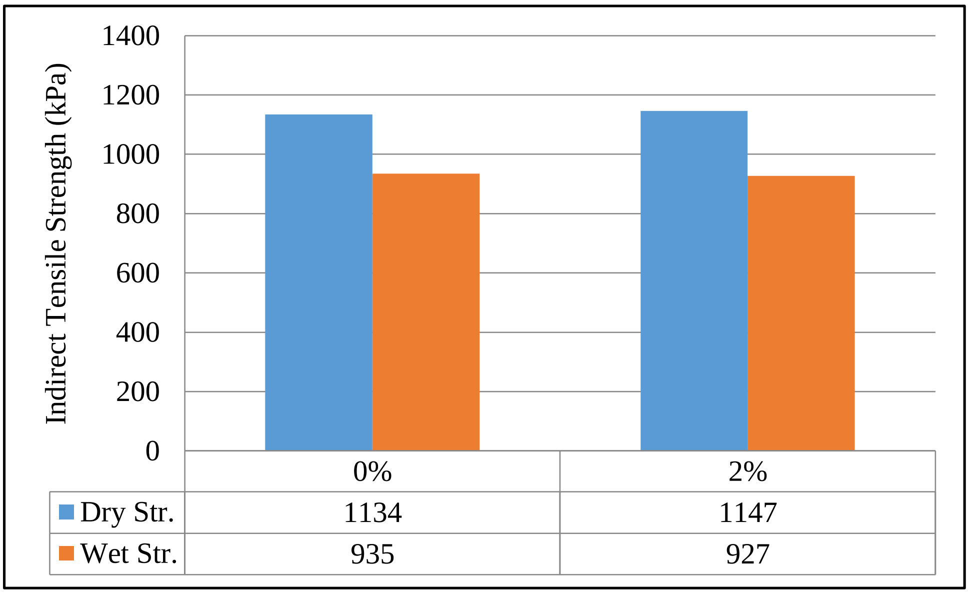

Figure 2. Indirect Tensile Strength (ITS) for dry and wet conditioned samples.

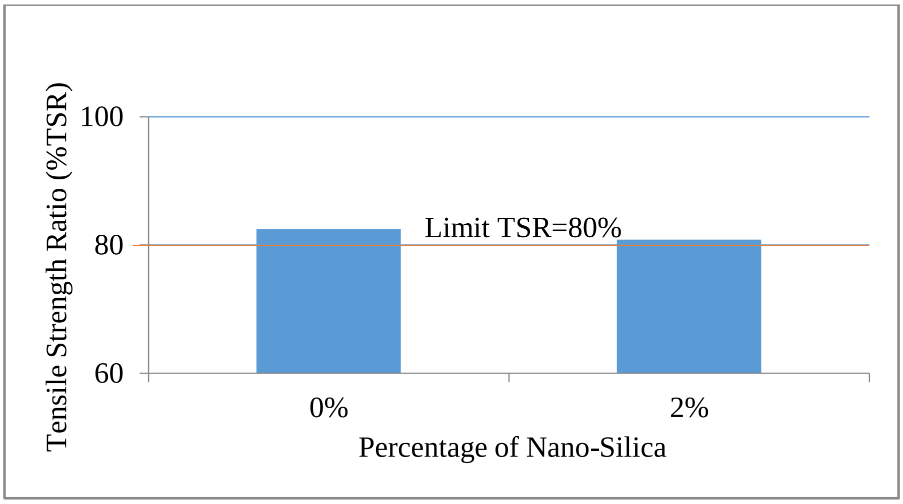

Figure 3. Tensile Strength Ratio (TSR) value for 0% and 2% NSMB.

Figure 3 shows the TSR value for both mixes; the TSR value for mixes with 2% NS (80.8%) was slightly lower than the TSR value for 0%NS mixes (82.5%). However, the result showed that both mixes meet the minimum TSR value of 80% required by AASHTO T283.

3.3. Resilient modulus

Figure 4 shows the resilient modulus graph for pulse repetitive periods of 1000 ms, 2000 ms and 3000 ms. The mixture with 2%NS has higher resilient modulus values for all pulse repetition periods compared to the mix with asphalt 0%NS. When the pulse repetitive period of 1000 ms was applied, the value of resilient modulus for 0% NS mixture was 5,477.5 MPa while for the 2% NS mixture. For the 2000 ms pulse period, the resilient modulus values for 0% and 2% NS mixes were 4,594.75 MPa and 6,060.25 MPa respectively. When the 3000 ms pulse period was applied, the values of resilient modulus for 0%NS and 2%NS mixtures were 4,188.75 MPa and 5,644 MPa. The results showed that the addition of NS can improve the stiffness of asphaltic concrete mixes as indicated with the higher resilient modulus values for the mixes with 2% NS.

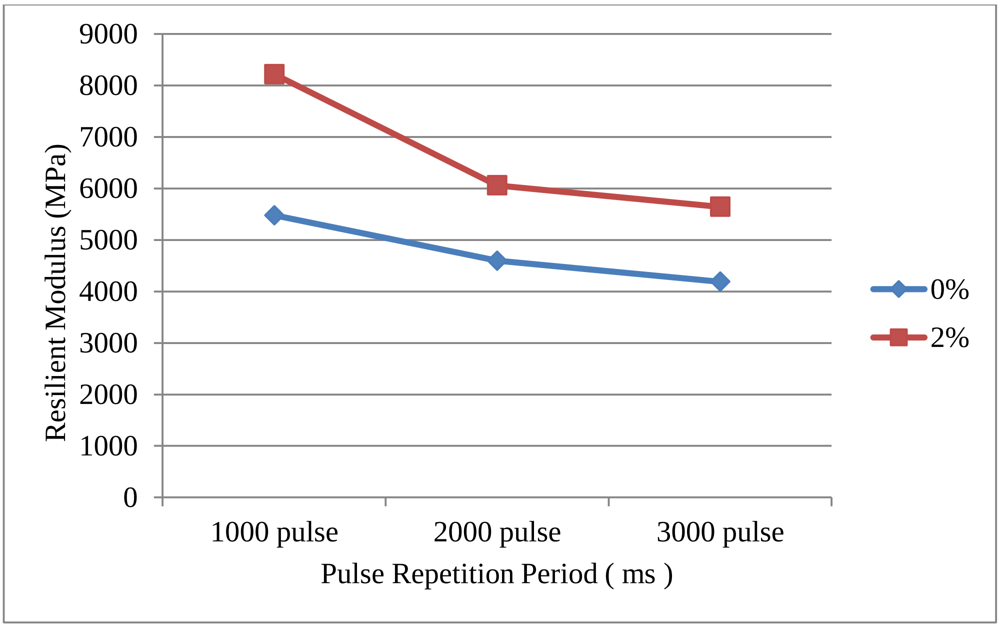

Figure 4. Resilient Modulus versus Pulse Repetition Period.

3.4. Rutting test

Figure 5 shows the graph for rutting depth versus number of cycles. The mixture with 2%NS has lower rutting depth compared to the mix with asphalt 0%NSMB. This result showed that the addition of NS could reduce the rutting depth of asphaltic concrete mixes.

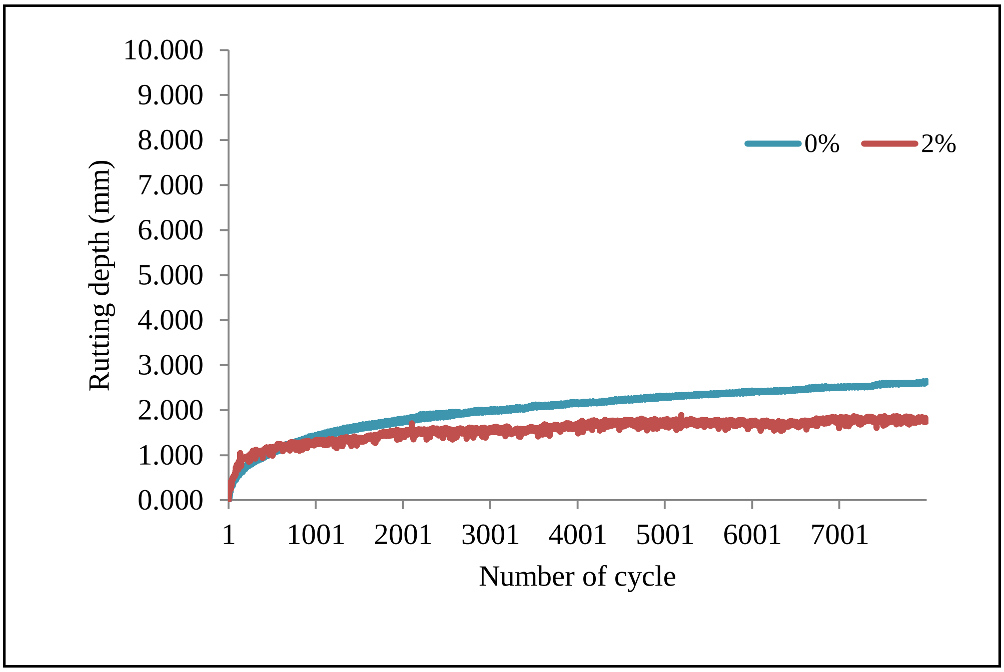

Figure 5. Rutting depth versus number of load repetition cycles.

Table 7 shows the rutting depth for both 0% and 2% NS asphaltic concrete mixes. The result showed that the rutting depth decreased by addition of NS in the asphaltic concrete mixes. The addition of 2%NS reduced about 33.0% of the rutting depth compared with the 0%NS mix. It can be concluded that the addition 2%NS on asphaltic concrete mixes can enhance rutting resistance and produce better quality of asphalt mixt. The rate of rutting for both of 0%NS and 2%NS mixes is also showed in Table 6. This result showed that the addition of 2%NS lowered the rate of rutting compared to 0%NS mix. The rate of rutting is reduced by 67.58% due to the addition of NS. This result showed that asphaltic concrete mix with 2%NS has a better performance for rutting resistance compared to asphaltic concrete mix with 0%NS.

Table 7. Rut depth and rate of rutting.

Type of mix	Rutting depth	Rate of rutting
Mix with 0%NS	2.637 mm	0.438 mm/hr
Mix with 2%NS	1.767 mm	0.142 mm/hr

4. Conclusion

Based on the experimental results on this study, the following conclusion can be made:

1) The moisture susceptibility performance for 2%NS is above the required minimum TSR ratio of 80%.
2) The stiffness of the asphaltic concrete mix increased by addition of 2% of NS in the mixture.
3) The rutting resistance increased by 30% by addition of 2% of NS in the mixture.

It can be concluded that the addition of nanosilica is beneficial to the dense asphaltic concrete mix, as the laboratory evaluation indicate improved performance in stiffness and rutting resistance.

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